Insights into the Complexity of Structural Fire Response from Repeated Heating Tests on Post-Tensioned Concrete

Cover page

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ABSTRACT

This paper extends discussion of previous research presented by the authors on post-tensioned (PT) concrete flexural elements in fire. Tests on two monostrand, continuous PT concrete slabs (one with an unbonded tendon and the other bonded) exposed to constant incident heat fluxes while under sustained load are reviewed and discussed. During testing these slabs demonstrated a distinct time-deflection response in heating and cooling consisting of five phases. For the first time, this paper gives the results from these unique slab tests during a second thermal cycle. The novelty of this study is that it was performed in an attempt to observe and better understand the thermal straining effects that contributed to the observed five-phase deflection response under first heating – illustrating many inter-related mechanisms that contribute to the complexity of the observed deflection responses. The resulting discussion is provided to advance the overall understanding of the response of real concrete structures (as opposed to isolated elements) in fire, and will hopefully assist structural fire modellers to validate (or otherwise) their modelling capabilities.

INTRODUCTION AND BACKGROUND

Performance based structural fire design methodologies for steel-concrete composite structures have greatly advanced in recent years. Such approaches are possible because comprehensive data sets exist from a range of large-scale structural fire experiments; these enable practitioners to support computational models usef to undertake performance assessments, analyses, and designs with relative confidence. As result, the number of full frame fire-engineered steel-composite structures continues to grow, with enhanced safety and optimized protection measures [1]. However, other structural typologies such as reinforced concrete frames and shear wall structures lack a similar amount of large-scale structural fire test data needed to inform model development, validation, and verification. This may limit the advancement of performance based structural fire design solutions for concrete structures. To shed light in this area, specifically for post-tensioned (PT) concrete flat

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slab structures, a series of loaded, three-span continuous PT concrete slabs were tested under sustained load and exposure to high temperatures at the University of Edinburgh between 2011 and 2014 [2]. The test series included both an unbonded and bonded monostrand stressed prestressing steel tendons (embedded at the centre of the slabs) and to the knowledge of the authors are the first such tests to incorporate axial, vertical and rotational restraint across multiple spans, whilst still accounting for bonded or unbonded tendon configurations [3]. The tests included as many complexities of real PT concrete construction as possible. A test schematic is shown in Figure 1; slab reinforcement details are given in Figure 2. The parabolic draped tendon resulted in an eccentric prestressing force at mid-span. The slabs were heated in their central spans using radiant panels that imposed a localized, constant incident heat flux.

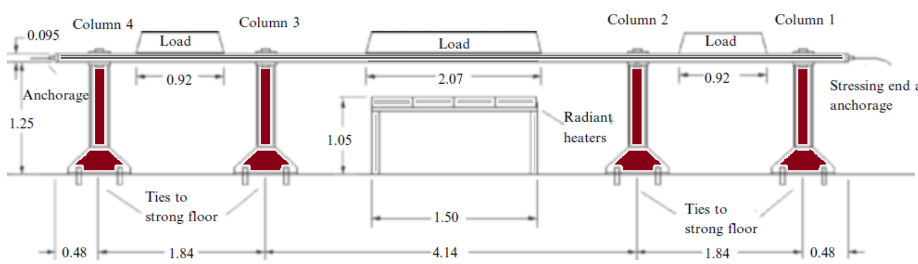

Figure 1. Test set up and geometry (front elevation, dimensions in m).

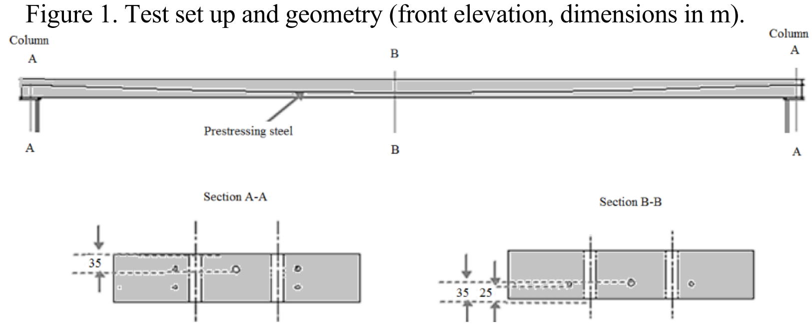

Figure 2. Steel reinforcement profile in concrete slabs (elevation and sections, dimensions in mm).

During testing the slabs demonstrated a complex, five-phase response (in heating and cooling); this is shown in idealized form in Figure 3. A detailed discussion of each phase has been given previously [3] and should be reviewed for additional context.

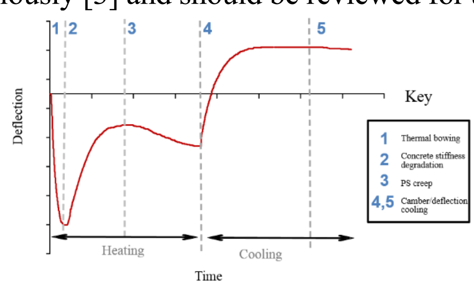

Figure 3. Idealized central span deflection vs time for constant incident heat source (+ive = camber).

Modelling the observed behavior is clearly challenging. The test deflection patterns were hypothesized as being influenced by a range of thermal and physical mechanisms, including load-induced thermal straining (LITS) [2]. LITS involves straining induced by stress concrete when exposed to high temperatures during the first exposure to heating [4]. As such, LITS strain effects should be absent under repeated heating, provided that the stress and heating levels are not exceeded. LITS is of significant interest to the structures in fire community, both qualitatively and quantitatively [4-8]. The practical significance of LITS for structural fire response has been debated within the modelling community, as has its impact on structural performance of concrete in fire tests. There is consensus that thermal straining under load (stress) involves a combination of plastic strains, and that these must incorporate 'transient' straining mechanisms [8]. A detailed discussion of LITS is available elsewhere [7][8]. The motivation in the current study is to use previously performed but unpublished testing performed by the authors to highlight the potential significance of LITS effects in concrete structures exposed to fire. The hope is that this might help to advance the understanding of concrete structures in real fires, and might assist in the development of advanced, validated computational modelling capabilities.

MOTIVATION

It is widely accepted that LITS occurs only under load and during a first heating cycle, and thus that it is absent should a material be heated for a second time. The authors previously presented fire tests on PT concrete slabs [2]; however two of these slabs were allowed to cool before experiencing any obvious signs of structural failure, and were subsequently subjected to a second fire exposure. This was done for one unbonded and one bonded PT concrete slab (with a total testing time of only 48 hours). The slabs were allowed to cool to ambient after the first heating test. They were then heated again to observe the impact of thermal straining effects and to try to better understand the other physical mechanisms at play which contributed to the observed five-phase deflection response in first heating (see [3]). These second heating tests are presented here for the first time.

EXPERIMENTAL PROGRAM AND METHODOLOGY

Reference [2], related to the first heating tests on the noted slabs, provides a detailed overview of the test set up, preparation, and detailed information pertaining to instrumentation, overall dimensioning, and ambient material parameters. The important information pertaining to the second heating is repeated herein where necessary. At all stages of experimentation: temperature was recorded through K-type thermocouples, which were predominately located in the central span (Figure 1) at mid span, quarter points of the slab and near columns; these were distributed over the slab depth at soffit, steel reinforcement, and top surface; a thermal camera was used to measure soffit temperatures; axial and rotational restraint from the supporting steel columns was monitored by calibrated foil strain gauges mounted on the column faces; tendon stress levels were monitored through two load cells at both dead and live slab ends; deflection was measured using five string pot displacement gauges; and three digital SLR cameras were used to monitor movement of columns and slab deflections by digital image correlation. As-constructed drawings are given in Figures 1 and 2. The concrete was C40/50 with predominately limestone aggregates, mild steel reinforcement was of 600 MPa yield strength, 10 mm diameter deformed bars with 25mm axis distance concrete cover, and prestressing steel was 1860 MPa grade 12.5mm diameter strand at 35 mm axis distance concrete cover. All slabs were loaded on all three spans using lead weights leading to a test load ratio of 0.32 and 0.42 for the bonded and unbonded slabs, respectively. The bonded slab, although constructed similarly, has higher ambient strength due to strain compatibility assumptions.

FIRST HEATING CYCLE

Both slabs were heated (in both heating cycles) by imposing a constant incident radiant heat flux of about 35 KW/m^2 using a radiant heating array. The slabs were first heated until the internal prestressing steel reached approximately 350^{o}C (the critical temperature for prestressing steel in Europe), and were then allowed to cool to ambient over 24 hours. After first heating and cooling both slabs exhibited a degree of damage, as shown schematically in Figure 4. This damage is important in understanding the observed response during second heating. Transverse cracking occurred adjacent to the supports, this was nearly twice as deep in the unbonded slab (extending 60 mm from the unexposed surface at a total depth of 95 mm) as opposed to the bonded slab (extending 30 mm from the unexposed surface at a 95 mm depth). The bonded slab developed a longitudinal crack that arrested outside the heated zone, and included a small spalled zone. In both slabs a transverse crack developed on the boundary of the heated soffit of the slab; all cracks were less than 1 mm wide.

Figure 4. Exaggerated schematic of slab damage after first heating for each slab (crack widths <1 mm).

SECOND HEATING CYCLE

Once cooled to ambient temperature, the slabs were again heated (under the same sustained imposed load) until the prestressing steel reached a temperature of 427^{o}C (the critical temperature for prestressing steel in North America). The slabs were then allowed to cool and were unloaded and de-stressed. The resulting deflection response during second heating (noting that both slabs were exposed to the same heating intensity) is illustrated for both slabs and both first and second heating cycles in Figure 5. No remarkable observations were made during cooling other than those discussed previously [2], and therefore only the heating portion is shown. The slabs recovered deflection of their thermal bowing deformation during cooling.

The second heating deflection response (mostly) followed the expected idealized five phase deflection responses seen during the first heating cycles (see Figure 3). During second heating the slabs showed: (1) a slower thermal bowing deflection rate during the initial stages of heating; (2) greater deflection of the unbonded PT concrete slab in the thermal bowing stage than the bonded slab, (3) a downward deflection increase after 2 hours for the unbonded configuration; and (4) a marked reduction in the camber growth for both slabs on cooling. These differences highlight the complexity of physical and thermal behavior in PT concrete in fire.

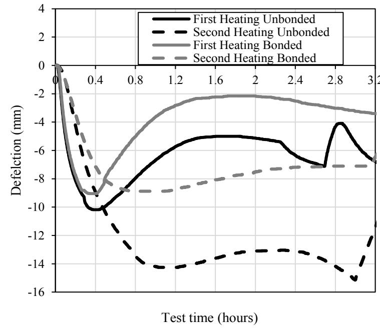

Figure 5. Deflection response of central span of PT concrete slab exposed to two repeat heats (note that deflection is relative to test start and positive is camber).

(1) Slower Rate of Thermal Bowing during Initial Stages of Heating

The deflection rate response of the concrete was less in second heating. Concrete during first heating loses moisture. This was visually confirmed by migration of pore water to unheated (cooler) portions of the concrete, see Figure 6. This migration behavior was absent in the second heating cycle as most of the free moisture had evaporated. The reduced moisture also results in a more rapid rise in temperature at the level of the prestressing tendon.

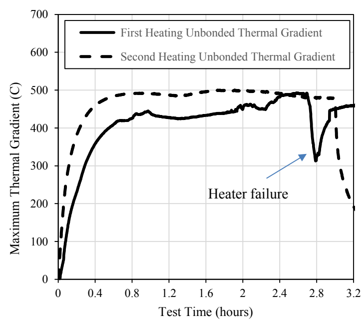

Figure 6. Tendon temperatures for the unbonded PT concrete slab for both first and second heating.

One might expect that the more rapid rise of temperature should indicate a faster climb in deflection from a steeper thermal gradient in second heating. That action was not directly observed for both repeat heating tests. While this behavior influences the deflection response of the slab, it does not appear to dominate the deflection behavior at the start of the test. The behavior instead appears dominated by a lower thermal expansion of the thermally pre-damaged concrete. This can be hypothesized [4] as less thermally stable concretes (those with limestone for example which these slabs were, see [9]) will have a reduced thermal expansion and consequently here, less bowing deflection. This is also made more profound when the consideration of reduced stiffness of thermally damaged concrete (see [9] for material testing using this and similar concretes) is considered. The aggregate and concrete type clearly can have a dominating influence on the initial stages of deformation of a heated concrete slab.

(2) Greater Deflection of the Unbonded PT Slab during Thermal Bowing

The unbonded slab illustrated considerably more deflection than the bonded slab during the second heating cycle. Upon cooling, both slabs recovered much of the bowing deflections. After both heating cycles, unloading, and prior to distressing, the unbonded slab showed significantly more remaining camber than the bonded slab (differing by about 2 mm), despite the same tendon drapes (as physically verified after testing). The deflections observed during thermal bowing represent a recoverable response of both the concrete and the embedded reinforcing steels – but this response between slabs obviously differs, and the only difference between the slabs, are their tendon bond and prestress relaxation states.

The differences can be explained by considering that the bonded slab only experienced localized tendon stress relaxation effects due to the local placement of radiant heaters; with stresses shed to the bonded steel (non-prestressed) reinforcement. This occured over less than half of the center span of the slab. While the bonded tendon was afforded some relaxation where it was heated (which cannot be directly measured or quantified), outside the heated region the tendon may maintain the majority of its original prestress (as partly confirmed by no observed changes in load cell readings at either the dead or live and anchorages, and post-testing confirmation that full grouting of the tendon duct had indeed occurred).

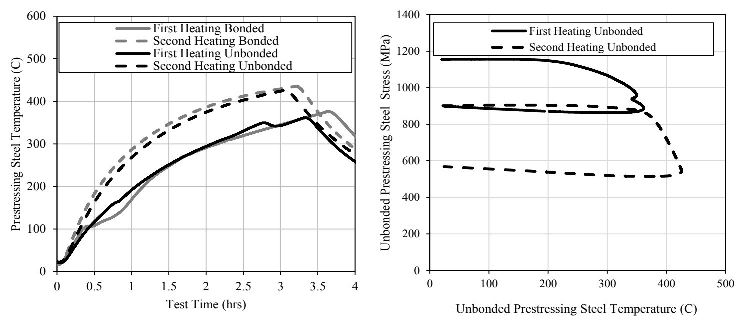

Figure 7. (a) Prestressing steel temperatures during heating, and (b) unbonded prestress relaxation of during repeat heating (bonded slab data not shown as there was no observable prestress relaxation.

The bonded tendon was therefore capable of balancing more load in areas outside the heated regions, where the unbonded slab tendon uniformly relaxed over the full length of the entire slab (including unheated regions) being unable to balance as much load, and hence expected to have greater overall deflection. The slab end-to-end stress relaxation for both heating cycles for the unbonded slab are shown in Figure 7b. This is a key difference between the two bond types slab behavior in fires.

Additionally, since the unbonded slab experiences more damage at the supports of the slab (likely as a result of the central span deflecting more), it is also hypothesized that the unbonded concrete slab had less rigid connections at the column supports during the second heating cycle; this in turn promoted more deflection.

(3) Downward Deflection Increase of the Unbonded PT Slab after 2 Hours

Figures 7 and 8 also illustrate that in both the bonded and unbonded tests the prestressing steel reached approximately the same temperatures with time. Likewise during repeat heating – indicating good test control, repeatable thermal exposures, and accurate placement of the instrumentation. These data also confirm that in the unbonded concrete slab, the prestress showed negligible relaxation effects until it reached its previous maximum exposure temperature (seen during the first heating cycle). After reaching that point the steel subsequently began again to relax. This relaxation (which reduces the ability to balance load) promotes more deflection of the slab. If the prestress state of the tendon was less than the original level during first heating, and below the maximum exposure temperature, it is expected that there should appear minimal creep relaxation deformation in Figure 7b (much like LITS is said to occur). Once the temperature exceeds its previous maximum, the creep relaxation appears to pick up where it last finished during the first heating cycle, and downward deflection dominates again. A comprehensive creep model to describe the prestressing steels used for this study has concurrently been developed [11], which helps to show the importance of explicit consideration of prestressing steel creep in any future UPT concrete structural fire modelling endeavors. In any case, these data show that thermal straining effects for prestressing steel can dominate the behavior of PT concrete slabs in fire.

(4) Reduction in the Post-Heating Camber Growth for both Slabs

The marked reduction in camber growth after thermal bowing of the deflection is observed in Figure 5. As hypothesized, if the maximum temperature of the concrete from the first heating cycle were not exceeded in the second cycle, this deformation camber action – if it is influenced by LITS – would be expected to be absent in the second heating cycle. In both slabs there is minimal cambering that occurs in the second heating; this is less than 2 mm after the thermal bowing phase. In comparison to first heating, where the value was about 7 mm. The action of camber growth can have influence from the neutral axis of the concrete shifting with the reduced stiffness of the thermally damaged concrete – this was seen in the first heating and is discussed in [2]. That action would not be expected to contribute much in second heating, since the neutral axis has already largely shifted during the first heating cycle. The contribution of both thermal straining effects and the neutral axis shift appear negligible beyond the initial stages of heating in both heats, but do appear to dominate in the initial stages of heating. That is before they are apparently overtaken in importance by the effects of creep of the prestressing steel.

CONCLUSIONS AND DISCUSSION

Repeat buildings fires in the same location are certainly not frequent; the second heating cycles imposed herein were intended not to simulate any practical reality, but rather to interrogate the physical reasons for the observed deflection histories for PT concrete slabs of both bonded and unbonded configurations [3], and further illustrates the complexity of PT concrete structures (or perhaps concrete structures in general) in fire. The predominant form of thermal straining effect (in the current case) was shown to be creep of prestressing steel. Once prestressing steel creep begins to accelerate, in all heating cycles, the slabs begin to deflect downward at pace. However, in the early stages of heating, deformation from thermal straining effects in concrete, possibly from LITS or from different coefficients of thermal expansion (although these two effects are complex, and hard to unpick, particularly for stressed and heated concrete) seem to play a larger role than tendon creep.

With the requisite data now available, attempts could be made to computationally model the presented tests; however, the complexity of these systems still prohibits even certain qualitative explanation of physical and thermal mechanisms described herein, let alone quantitative analysis. It may therefore be questionable if available structural fire modelling techniques are yet able to demonstrate a capability to capture these complexities, and how these complexities might be interrelated. Currently, simple prescriptive fire resistance tests are typically extrapolated from small scale isolated member tests to describe a full system behavior for PT concrete.

The thermal and physical mechanisms observed in the testing presented herein represent man of the factors that could be expected to play roles in real PT concrete structures. Prescriptive rules – regardless of tendon bond – cannot possibly capture these complex mechanisms and interactions. More realistic structural testing of PT concrete needs to be performed to confirm the severity and degree of impact thermal straining effects on concrete.

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